Formation mechanisms and remediation techniques for low-efficiency artificial shelter forests on the Chinese Loess Plateau

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Abstract: The construction of artificial shelter forests (ASFs) has resulted in substantial ecological, economic, and societal benefits to the Chinese Loess Plateau (CLP). However, the health and benefits of ASFs are being increasingly threatened by the formation of low-efficiency artificial shelter forests (LEASFs). In this study, LEASFs are systematically analyzed in terms of their status, formation mechanisms, and developmental obstacles. The key restoration techniques and schemes were summarized to improve the quality and efficiency of LEASFs. LEASFs are formed by relatively complex mechanisms, but they arise mainly due to poor habitat conditions, improper tree species selections, mismatch between stands and habitat, extensive forest management measures, and human interferences. The restoration and improvement of LEASFs are hindered by water deficits, mismatch between stands and habitat, single management purpose, and low efficiency. LEASFs are becoming more complex due to their wide range, the challenges associated with their restoration, and insufficient technological measures for their restoration. The key techniques of the quality and efficiency improvement of LEASFs include basic forest tending methods, near-natural restoration, multifunction-oriented improvement, and systematic restoration. An understanding on the formation mechanisms of LEASFs and a scientific approach toward their restoration are urgently needed and critical for the ecological protection and high-quality development of LEASFs on the CLP. Based on these analyses, we recommend strengthening the monitoring and supervision of LEASFs, considering the bearing capacity of regional water resources, implementing multiple restoration techniques, promoting multifunction-oriented ecological development, and exploring new management concepts to achieve the sustainable development of ASFs on the CLP.

Keywords: low-efficiency artificial shelter forests; restoration; forest management; multifunctional forestry; near-natural forestry; Three-North Shelter Forest; Chinese Loess Plateau

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1 Introduction

The Chinese Loess Plateau (CLP) is known as the birthplace of Chinese civilization (Zhu et al., 2018), with more than 1.0×10^8 people living here (Fu et al., 2017). The survival and well-being of the people living there is closely associated with the health of the natural environment of the CLP. With the implementation of a series of national restoration programs (Wang et al., 2018), large

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areas of artificial shelter forests (ASFs) have been constructed on the CLP. ASFs have become important ecological barriers (Zhu et al., 2004), resulting in immense ecological, economic, and societal benefits for local areas (Xiao et al., 2019; Zhu and Zheng, 2019). Improving the quality and increasing the efficiency of ASFs have become key issues for achieving ecologically sound development projects on the CLP.

With the purpose of solving long-term problems on the CLP, such as low vegetation coverage, severe soil erosion, and ecosystem degradation, a series of projects have been implemented, including the "Three-North Shelter Forest", "Natural Forest Protection", and "Grain for Green" projects (Liu et al., 2017; Wang et al., 2018). These measures have achieved remarkable outcomes, such as effective improvement of ecological environment (Jiao et al., 2005), continuous increasing forest coverage (Liu et al., 2017), significant reduction in soil erosion and sediment transport by the Yellow River (Wang et al., 2015), and large reduction in carbon emissions (Deng et al., 2014, 2019). However, the establishment of ecological restoration projects has also presented new problems, especially those associated with ASFs. On the one hand, increasing the area of ASFs has resulted in substantial reductions in watershed runoff (Yu et al., 2009) and increased forest water consumption. On the other hand, large areas of ASFs also have growth problems, such as poor stand stability (Hao, 2012), unsuitable forest structures, and a lack of understory regeneration (Ahmad et al., 2018). In addition, especially in recent years, large areas of inefficient or even degraded forests have been created (Guo et al., 1998). These forests, known as low-efficiency artificial shelter forests (LEASFs), tend to show a gradual but severe decline in their functions (Wang, 2010) because of poor ecological conditions, unscientific forest management measures, global climate change, and mature stand physiology (Guo et al., 1998). The ecological restoration achievements of ASFs are compromised by LEASFs, threatening the protection of human life and property and the goal of achieving ecologically sound development of the CLP. Since 2015, a series of works on LEASFs have been carried out by the National Forestry and Grassland Administration of China, including investigations of the status of degraded shelter forests, the construction of experimental areas, and the formulation of technical specifications for their transformation. Many related studies and experiments have been carried out, comprising researches focused on the concepts, definitions, formation mechanisms, and restoration techniques and measures for LEASFs (Li et al., 2009; Liang, 2019; Bi and Hou, 2021). Improving the quality and efficiency of LEASFs has become an important part of forestry development and ecological construction on the CLP.

Systematic efforts based on experiences with LEASFs on the CLP are urgently needed to provide valuable theoretical support for the sustainable development of ASFs in the future. In this study, we systematically analyze LEASFs on the CLP from the perspective of their formation mechanisms, current status, advances in restoration, future challenges, and key techniques or models for restoration. Our study also offers scientific suggestions for the remediation of LEASFs and the improvement of ASFs in the future, thereby providing scientific and technological support for the ecological management and high-quality development of the CLP.

2 Influencing factors and formation mechanisms of LEASFs on the CLP

The formation of LEASFs on the CLP is driven by many interrelated factors (Zhu, 2013). These influencing factors can be divided into the following four categories: human interferences, habitat conditions, stand conditions, and disasters (Fig. 1). Resulted by these factors, LEASFs with unbalanced forest structure and stability and retarded growth would enter a recession stage prematurely or transition to the recession stage quickly, finally resulting in death, poor growth, and other phenomena of forests. Ultimately, the functions of ASFs, such as carbon sequestration, wind breakage, sand fixation, and water conservation, would decline or cease altogether. The formation mechanisms of LEASFs are shown in Figure 1.

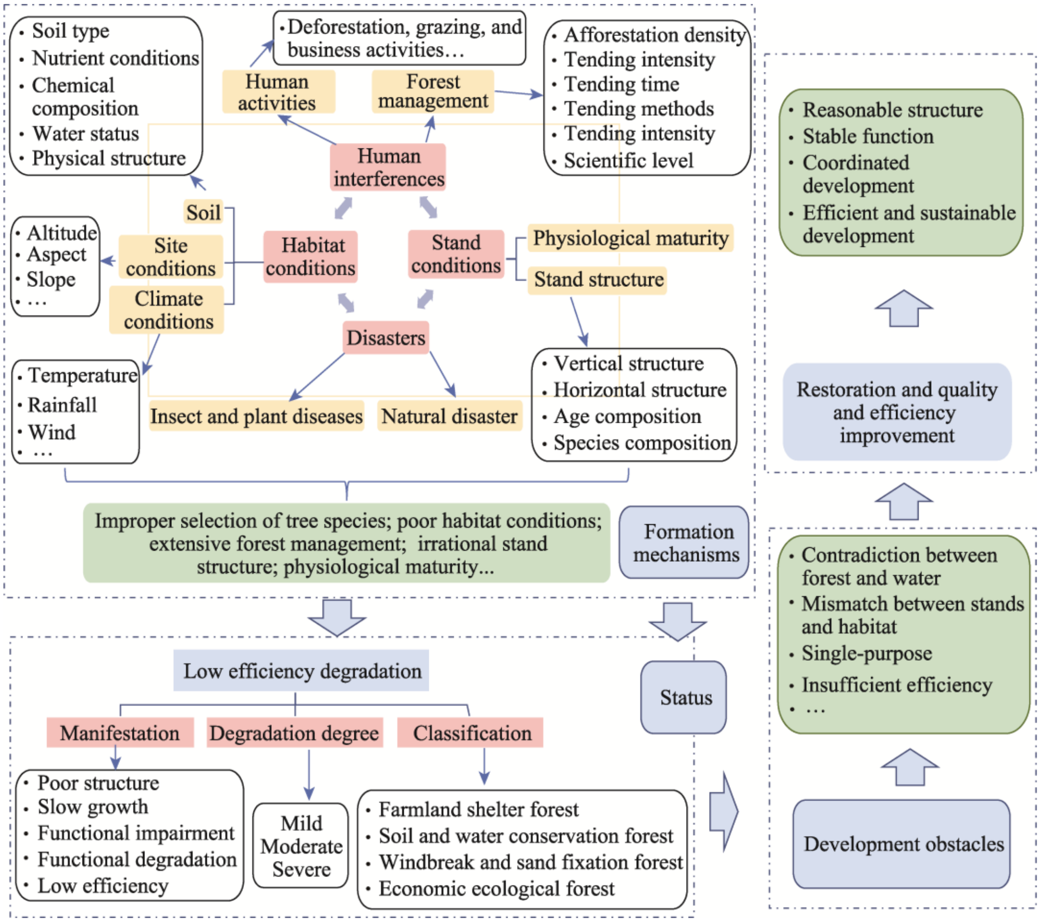


Fig. 1 Formation mechanisms and performance types of low-efficiency artificial shelter forests (LEASFs) on the Chinese Loess Plateau (CLP)

2.1 Poor habitat conditions, improper selection of tree species, and mismatch between stands and habitat

Poor habitat is considered as one of the major factors in the formation of LEASFs on the CLP. The survival and growth of plants require necessary materials provided by their natural conditions, such as water, light, temperature, and nutrients. The nutrient conditions of soils are important factors affecting stand health. The protected forest plantations on the CLP mainly come from abandoned farmland or other lands with poor soil quality. Soil fertility deficiencies have become a challenge for the healthy growth of trees. Besides, most of the ASFs are semi-arid regions and have an average annual precipitation of approximately 400 mm. Insufficient water support may not only prevent natural regeneration (Zhu et al., 2006) but also stunt the growth of trees (resulting in the formation of "little old trees") (Jiang et al., 2006). In addition, the improper selection of tree species for planting also exacerbates the formation of LEASFs. Approximately 40.00% of the new arbor forests are distributed in the "Three-North Shelter Forest" area with the average annual precipitation of less than 400 mm, and unhealthy forest area accounts for 26.40% of the total afforestation by the "Three-North Shelter Forest" project (Xiao et al., 2019; Zhu and Zheng, 2019). Furthermore, the planting of afforestation tree species in unsuitable climatic conditions for growth is responsible for the formation of LEASFs. As the main afforestation tree species in early forest management on the CLP, the growth decline of poplar species is mainly caused by insufficient water supply in the planting areas.

2.2 Extensive forest management and frequent human and natural interferences

Extensive forest management would also promote the formation of LEASFs from forestation techniques and forest tending. At the beginning implementation stages of projects on the CLP, the afforestation density of most plantation forests is 10,000 trees/hm^2 or 6700 trees/hm^2. The high stand density inevitably causes competitions between adjacent trees for nutrients and growing space. The density of stands strongly affects forest growth or even results in forest degradation. Large areas of artificial forests that consist of a single species of the same age have low biodiversity and poor growth. Inappropriate forest management after afforestation also affects the health of forests. In the Wutai Mountain (Shanxi Province), there are large areas of low-functioning *Larix principis-rupprechtii* forests because of extensive management techniques (Zhang et al., 2007).

Frequent extreme weather conditions, including high temperature, drought, climate anomalies, and successive years of drought and precipitation, also harm vegetation restoration on the CLP (Wang et al., 2017; Sun et al., 2020). On the windward side, frequent strong winds result in crown deviation. Cold drying in winter can cause frostbite or lead to the death of trees due to freezing. Frequent logging, grazing, and land reclamation have destroyed the structure and nutrients of lands planted as protected forests. Severe soil erosion and the loss of soil nutrients are the main human-driven factors that have led to the development of LEASFs. Rodents and rabbits occur frequently in the forest areas of *Pinus tabulaeformis*, *Larix gmelinii*, and *Pinus armandii* in Gansu Province, which seriously harm the forest growth.

2.3 Unreasonable stand structure and physiological maturity of forests

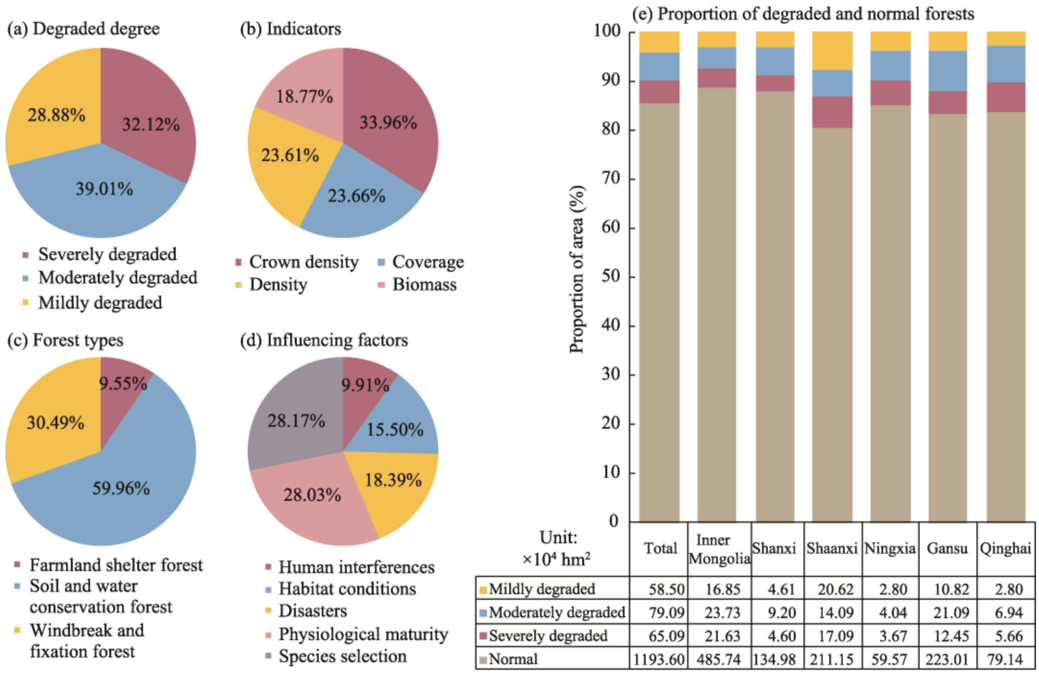
Reasonable stand composition and structure are the key to forest function; improper stand composition and structure will cause poor tree growth, insufficient benefits, and functional degradation. These phenomena will be exacerbated by human and natural conditions (Jiang et al., 2006; Song et al., 2009). In the 1990s, the second-generation forests in Ningxia Hui Autonomous Region were destroyed by cattle (National Forestry and Grassland Administration of China, 2017). Further, almost all the species of the farmland shelterbelts constructed in the early stage of the "Three-North Shelter Forest" project consist of poplar trees, and the scarcity of shrubs and herbaceous under the forest canopy also leads to low functional stand benefits.

The physiological maturity of stands is the main reason for the degradation of large-scale ASFs on the CLP. The "Three-North Shelter Forest" project has been implemented since 1978. The forests in the first stage of the "Three-North Shelter Forest" project have been preserved for approximately 40 years, and those in the second stage have been preserved for over 25 years. In the maturity stage or even in the recession stage, the quality of stands declined rapidly and the physiological functions also decreased. In the northern region of Shanxi Province, a large area of *Populus simonii* forests has entered a natural maturity period (Yan et al., 2021). As for the "Three-North Shelter Forest" area, shrub forests with a proportion of 43.00% have a shorter growth cycle than tree-dominated forests, and mature forests in 40% of farmland shelter forests need to be restored (National Forestry and Grassland Administration of China, 2017). In addition, unreasonable afforestation measures and unsuitable natural conditions can also accelerate the physiological maturity of ASFs.

3 Achievements and restoration status of LEASFs on the CLP

On the CLP, LEASFs are widely distributed with large covering areas, complex formation mechanisms, multiple types, and increasingly restoration difficulties. A survey conducted by the National Forestry and Grassland Administration of China (2017) indicated that approximately 14.52% of the shelter forests on the CLP were degraded (Fig. 2). Shaanxi Province had the highest proportion of degraded forests, accounting for approximately 19.70% of the total degraded forest area on the CLP. Inner Mongolia Autonomous Region had the largest area of degraded forests, at approximately 62.22×10^4 hm^2. Qinghai Province had the most extensive

formation of LEASFs among the degraded forests on the CLP (Fig. 2e). The areas of severely, moderately, and mildly degraded forests on the CLP were 65.09×10^4, 79.09×10^4, and 58.50×10^4 hm^2 (Fig. 2e), accounting for 32.12%, 39.01%, and 28.88% of the total forest area, respectively (Fig. 2a). According to the statistics, the five major reasons for the formation of degraded forests on the CLP were related to physiological maturity, habitat conditions, tree species selection, disasters (diseases, pests, and rodents), and improper human interferences. Species selection and physiological maturity were the major factors for forest degradation, accounting for the greatest proportions, i.e., 28.17% and 28.03%, respectively (Fig. 2d). Improper human interferences accounted for the lowest proportion, at 9.91% (Fig. 2d). As for the main types of shelterbelts, the farmland shelterbelt forest covered an area of 19.36×10^4 hm^2, the soil and water conservation forest covered an area of 121.54×10^4 hm^2, and the windbreak and sand fixation forest had an area of 61.79×10^4 hm^2 (Fig. 2c). Overall, the forest degradation situation was still severe and quite different in each region of the CLP. There were 117.35×10^4 hm^2 of young- and middle-aged plantations in the northern area of Shaanxi Province, accounting for 54.80% of the total plantation area (Yan et al., 2021). In all, there is still much work to do in restoring LEASFs on the CLP.



Unit: ×10^4 hm^2	Total	Inner Mongolia	Shanxi	Shaanxi	Ningxia	Gansu	Qinghai
Mildly degraded	58.50	16.85	4.61	20.62	2.80	10.82	2.80
Moderately degraded	79.09	23.73	9.20	14.09	4.04	21.09	6.94
Severely degraded	65.09	21.63	4.60	17.09	3.67	12.45	5.66
Normal	1193.60	485.74	134.98	211.15	59.57	223.01	79.14

Fig. 2 Analyses of the status of degraded artificial shelter forests (ASFs) on the CLP in 2017. (a), the proportions of different degrees of degraded shelter forests: severely degraded, moderately degraded, and mildly degraded; (b), the proportions of degraded ASFs in different growth indicators: crown density, coverage, density (the ratio of preserving plants to afforestation design plants), and biomass; (c), the proportions of areas of different forest types: farmland shelter forest, soil and water conservation forest, and windbreak and sand fixation forest; (d), the proportions of different influencing factors to forest degradation: human interferences, habitat conditions, disasters, physiological maturity, and species selection; (e), the proportions of degraded (severely degraded, moderately degraded, and mildly degraded) and normal forests in different regions on the CLP: Inner Mongolia Autonomous Region, Shanxi Province, Shaanxi Province, Ningxia Hui Autonomous Region, Gansu Province, and Qinghai Province. The data are from the National Forestry and Grassland Administration of China (2017).

4 Main challenges for the restoration of LEASFs on the CLP

4.1 Water resource deficiency and conflicts with forestry development

With the advancement of ecological restoration, the antagonistic relationship between water supply and forest water consumption has become increasingly prominent. Poorly planned

afforestation can result in high water consumption. Consequently, the vegetation carrying capacity is exceeded, further resulting in water deficit or severe drying of soil layers (Wang et al., 2012). Coordinating the relationship between forests and water resources has become a primary condition for the development of forestry on the CLP. Although the distribution of precipitation on the CLP is low and uneven, it is considered as the only source for plant growth. Therefore, under the trend of warm and dry climate, the water demand of growing forests is difficult to meet, especially those trees with high rates of evapotranspiration (Yang, 2018). In addition, the unreasonable distribution of water used for domestic, production, and ecological purposes and the unbalanced and unreasonable use and distribution of water in the upper and lower reaches of rivers have further exacerbated the water deficit for forests on the CLP.

4.2 Mismatch between stands and habitat

Mismatch between stands and habitat on the CLP is particularly prominent, gradually causing adverse consequences that can hinder the development of forestry. Due to the mismatch between stands and habitat, stand growth is reduced with low quality and limited natural regeneration, resulting in inefficient or even degraded stands. An undesirable distribution of trees, shrubs, and grasses will also lead to increased water consumption and soil degradation. In addition to violating the laws of geographical distribution of plants, there is a mismatch between vegetation and microclimate. For example, the early selection of poplar species in the Huajialing Mountain is not suitable for the high-altitude climate. The mountainous region has frequent windy activities and poor soil quality, which is not suitable for tree growth, resulting in low survival rate and growth recession across large areas.

4.3 Single management purpose and insufficient forest benefits of LEASFs

Based on the early forest management initiatives, ASFs were planted on the CLP with single management purpose of soil and water conservation, wind protection, or sand protection. Lack of consideration for other ecological functions and goals presents a challenge for maximizing forest benefits. Thus, poplar, locust, and other fast-growing tree species were selected to pursue short-term benefits. In addition, to maximize timber benefits, pure forests with a high initial density were chosen rather than natural forest structures, resulting in insufficient late-term development. The single development goal of large-scale ecological public welfare forests with the low efficiency benefits cannot meet the needs of socioeconomic development and people's livelihoods now. Broadening ideas for industry and considering a variety of potential economic, social, and other benefits have become key requirements for forestry development in the new era.

5 Key techniques for improving the quality and efficiency of LEASFs

5.1 Optimizing stand structure and composition via precise implementation of various forest tending measures

Adopting appropriate forest tending measures in different types of LEASFs (degraded degrees, growth indicators, forest types, and influencing factors) is key for achieving restoration and efficiency improvement in ecosystem functions and benefits. For different restoration types of LEASFs, six types have been outlined: replacement restoration, restoration by selective cutting and replanting, tending restoration, gradual restoration, enclosed restoration, and comprehensive restoration. These reference forest tending measures have been flexibly applied depending on the habitat (Zhang, 2017; Song, 2020; Yu et al., 2020). Therefore, we recommend that severely degraded forests should be reforested, moderately degraded forests should be replanted, and mildly degraded forests should be managed with appropriate pest control measures.

5.2 Promoting a ''near-natural forestry'' (NNP) concept

Natural restoration, artificial-assisted restoration, and ecological engineering are the three common traditional ecological restoration methods (Ren et al., 2019). The concept of NNP was initially proposed in Germany in the 19th century and was swiftly expanded throughout Europe

and the United States (Remeš, 2018). It was studied and applied in the 1990s and became the mainstream ideology in the new era (Shao, 1991; Liu et al., 1996; Zhang et al., 1996; Gao, 1999). Promoting NNF restoration techniques is of great significance for the restoration of LEASF. Nature-based solutions, consistent with the recovery concept of NNF (He et al., 2020), focus on the sustainable development to simultaneously meet the development goals of both human and the natural environment (Mussinelli et al., 2018). NNF emphasizes nature based on the theories of forest ecosystem stability, biodiversity, ecosystem multifunction, and buffering capacity. The main technical characteristics are selective cutting and natural regeneration, and the forest structure characteristics that mimic natural forest structures consist of the inclusion of multispecies and multilevel and different-aged forests to create mixed forests for sustainable and efficient management. Lu et al. (2017) proposed a logical framework for the overall analysis and decision-making for the near-natural restoration of four types of artificial forests: broadleaf forest, coniferous forest, coniferous and broadleaf mixed forest, and even-aged coniferous forest. This approach is based on understanding and respecting the laws of nature: giving priority for natural recovery and supplementing with reasonable human interferences. Increases in ecological functions and growth rates are achieved through the continuous optimization of stand structures. Wang et al. (2021) completed the evaluation of the near-natural state of five forest stands and proposed corresponding remediation measures according to the evaluation results by selecting 10 indicators related to stand structures, species composition, age, and dead wood and by adopting a combination of qualitative and quantitative methods. He et al. (2020) considered seed multiplication, assembly, and supplementary sowing techniques of native grassland species to be bottlenecks to the near-natural restoration of alpine grasslands, and proposed that a combination of soil nutrient augmentation and microbial regulation is an essential supplementary measure. Therefore, exploring the remediation of inefficient or degraded forests based on the near-natural management theories is of great significance.

5.3 Function-oriented restoration under the multifunctional forestry concept

The objective and concept of forest management have gradually transitioned from single objective-oriented forest management to a comprehensive consideration of the multidimensional functions and benefits of forests. Based on the near-natural management theory and approaches, multifunctional forestry management can meet the needs of social and economic development to the greatest extent by balancing and improving the various products and service functions of the ecosystem. There are two kinds of multifunctional forestry management depending on the focus: stand level and overall regional forest level. Developing multifunctional forestry management both at the stand scale (Ahmad et al., 2018) and regional scale (Wang et al., 2011) involves decision making with trade-offs. The trade-offs are related to functions such as carbon fixation, oxygen release, forest water supply, species protection, etc. (Carpentier et al., 2017; Strengbom et al., 2018); the overall optimization is based on meeting the needs of (one or more) dominant functions and considering other important functions (Wang et al., 2015). An in-depth and quantitative understanding is required to balance competing forest functions (Bennett et al., 2009; Dade et al., 2019) through consideration of potential forest ecosystem services and functions supported by site conditions and trade-offs (Resende et al., 2018). Forest structure adjustment is a necessary step to achieve the goal of multifunctional forestry management (Lu et al., 2017). Hao (2012) and Tian (2019) explored the decision-making process for multifunctional forestry management using *Larix Principis-rupprechtii* in the Liupan Mountains as an example. Huang (2020) reported that degraded poplar forests were transitioned to *Rhus Typhina* and *Forsythia suspensa* landscape forests and *Armeniaca vulgaris* economic forest in the Yunzhou District of Datong City, Shanxi Province.

5.4 Application of biological regulation, chemical regulation, and soil dry layer regulation

Systematic restoration is an effective way to realize the sustainable development of plantations. Soil ecosystem restoration for restoring LEASFs by adding exogenous substances, biological

regulation, and soil dry layer regulation should be considered. Soil nutrient conditions and forest health can be improved by promoting the physical and chemical properties of soils. Nitrogen addition (Yu et al., 2010), biochar amendment and exogenous mycorrhizal fungus addition (Ren et al., 2014), and humic acid addition (Li et al., 2020) have been used to improve forest soil conditions and promote forest growth. In addition, solving the dry soil layer problem is crucial for stand transformation and the improvement of forest functionalities. Soil moisture can be restored to a certain extent in the natural state (Wan et al., 2008) at a slow speed (Cheng et al., 2004). Fortunately, the recovery of soil moisture can be accelerated by artificial recovery. Regulation of the soil water deficit can be achieved in two ways: increasing soil water supply and reducing soil water consumption by population density regulation, land-use change, plant replacement, and adjusting biological coverage and physical coverage. Straw or grass mulching has effectively increased precipitation infiltration, reduced surface runoff, and inhibited evaporation of soil moisture in farmland and economic forest management applications (Huang et al., 2009; Cai et al., 2011). It also has importance as a reference for forest ecological protection (Wang and Guo, 2020). The combination of the engineering land preparation measures and three-dimensional configuration mode of shrubs and grasses can also regulate soil moisture and promote the rapid restoration of shrub-grass vegetation. In addition, suitable development of the understory plantings and breeding industries can also promote nutrient cycling and improve site conditions.

6 Suggestions for the quality and efficiency improvement of LEASFs

The vegetation coverage on the CLP has been greatly improved by the continuous advancement of ecological restoration projects with alleviated ecosystem degradation to some extent. However, the reduction of available land and the increase risk of vegetation carrying capacity have become the main obstacle for the ecological restoration on the CLP (Wang et al., 2021). Optimization of existing LEASFs has become the focus of ecological construction projects on the CLP now. A framework diagram for the quality and efficiency improvement of LEASFs on the CLP is shown in Figure 3. Suggestions for the quality and efficiency improvement of LEASFs on the CLP in the following four categories are proposed.

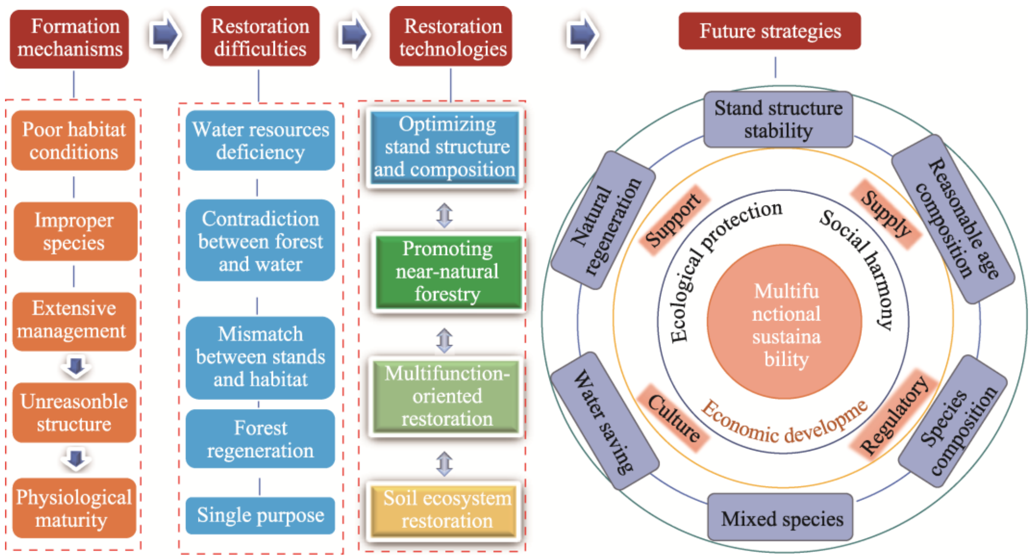


Fig. 3 Framework diagram for the quality and efficiency improvement of LEASFs on the CLP. This Figure is referenced and modified from Wang et al. (2021).

6.1 Strengthening the monitoring and supervision of LEASFs

This is a new challenge to improve the quality and efficiency of LEASFs on the CLP. Obtaining

adequate and reliable basic data (by field survey, remote sensing monitoring, etc.) for LEASFs on the CLP is a powerful way to guarantee the accurate implementation of scientific analyses and decision-making for the quality and efficiency improvement of LEASFs. Consequently, we advocate the following measures: (1) formulating scientific and reasonable criteria and investigation methods for LEASFs in the same accreditation standards; (2) investigating the background data of LEASFs in different regions of the CLP, including low-efficiency function types, spatial distribution, main influencing factors, and degrees of degradation; and (3) establishing representative long-term experimental plots to monitor the restoration of LEASFs. Many different advanced techniques are used to monitor the spatiotemporal variation in LEASFs to establish an airspace-earth coordinated monitoring network from the soil, stand, and air using multisource remote sensing monitoring, ecosystem network observation stations, and field sampling surveys. Through this effort, the current problems related to insufficient and unreliable data will be solved. This makes it possible to control the developmental trends of LEASFs in real-time and achieve the accurate restoration and improvement of their quality and efficiency.

6.2 Fully considering the bearing capacity of regional water resources

The shortage of water resources is a common and major obstacle to the high-quality ecological protection on the CLP. There are some problems need to be solved in the vegetation restoration and ecological development on the CLP, including the decline in soil moisture, the formation of dry layer in deep soil, and excessive consumption of groundwater. For the reasonable utilization of water resources, efforts can be directed via the following approaches: (1) identifying the water resource carrying capacity of vegetation in different regions; (2) clarifying the water cycle and water consumption in different types of forests; (3) reducing the wastage of water resources by optimizing stand structure and tree species composition; (4) fully utilizing precipitation resources by building reservoirs in forests and dams in the surrounding gullies; and (5) exploring the trade-off between the utilization of water by vegetation and the ecological protection functions of the vegetation. Overall, we should pay more attention to the consumption of water resources for ecological restoration and the bearing capacity of regional water resources. More techniques and methods should be explored to balance water resources utilization and ecological development.

6.3 Scientifically implementing various forest management measures and rehabilitation techniques

A lack of necessary management has led to damage to the growth and functions of some forests on the CLP. The restoration techniques used should be evaluated. Therefore, we suggest the following measures: (1) increasing special funds investment in forest tending and management, and strengthening the efforts to improve the quality and efficiency of LEASFs on the CLP; (2) assessing the effectiveness of existing restoration techniques and the feasibility of the regional extension of LEASFs on the CLP; (3) establishing rehabilitation demonstration plots in typical degraded areas to identify the transformation techniques and developmental directions of the different types of LEASFs; (4) actively promoting the "structure-based forest management" on the CLP; (5) establishing a suitable vegetation pool for local growth and cultivating good target tree species for planting on the CLP; and (6) replacing original tree species with native or suitable tree species and transforming the pure forest into the mixed forest. LEASFs can be restored through the precise implementation of these forest tending measures.

6.4 Promoting multifunctional-oriented construction and realizing the coordinated development of multifunctional service benefits

To achieve the high-quality and sustainable development of vegetation restoration on the CLP, we propose to implement these recommendations: (1) fully assessing the carbon sequestration potential and value contribution of ASFs on the CLP to meet the Chinese goal of emission peak and carbon neutrality; (2) fully considering other ecological regulation service functions (supply of economic products, ecotourism value, and forest health care) of forests during restoration; (3) balancing ecological benefits, social benefits, and economic benefits during forest development;

(4) adopting the concept of near-natural forestry and multifunctional-oriented management during the restoration and improvement of the quality and efficiency of LEASFs; and (5) exploring new multiinvestment and multioperation mechanisms for the construction of ecological projects with government-led social participation and multiple inputs from society. In summary, we hope to make efforts to achieve the high-quality development of LEASFs on the CLP and to achieve the coordination between ecological protection and economic development.

7 Conclusions

In our study, the formation mechanisms of LEASFs on the CLP are considered as complex, including poor habitat conditions, improper tree species selections, mismatch between stands and habitat, extensive forest management measures, and human interferences. Besides, water deficits, mismatch between stands and habitat, single management purpose, and low efficiency are summarized as the main obstacles for the restoration and improvement of LEASFs at present and in the future. According to the increasing complex status and restoration challenges of LEASFs, we considered basic forest tending methods, near-natural restoration, multifunction-oriented improvement, and systematic restoration as the key restoration techniques for LEASFs. Finally, for optimizing the existing LEASFs and avoiding new one generation, we need to not only strengthen the monitoring and supervision of LEASFs, but also pay more attention to consider the bearing capacity of regional water resources, scientifically implement various forest management measures or rehabilitation techniques, and promote the development of multifunctional-oriented forests in the future work.

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